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13. ABSTRACT *(Maximum 200 words)*

This report summarizes the activities in the use of linear piezoceramic linear actuators coupled with control methods and wing aeroelastic models to increase flutter speeds of wing/store configurations. The work resulted in the successful submission of three journal articles and the completion of three proceedings papers, one invited lecture, and the completion of one PhD dissertation. Our results examine the use of modern control methods (H infinity, loop transfer, LQG/LQR), applied to the wind/store flutter problem as modeled by a typical two-degree-of-freedom airfoil section coupled with the Jones' approximation to the Theodorsen function for the incompressible aerodynamic loads. Physical values are taken from the GBU-UB weapons system mounted on an F-16. Actuator parameters are those of a piezoceramic, linear stroke, wafer device. Store aerodynamics are ignored. Results produce a substantial increase in flutter speed, and allow consideration of the store release problem. Preliminary results and modeling for solving the 3-D version were also investigated.

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Fluid, Structure and Control Interaction

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Summary:

The focus of this work was to investigate an active method of enhancing the performance and robustifying the stability of a wing/store flutter suppression system. This work is built upon a wing/store flutter suppression system consisting of a decoupler pylon mounted store with pitch-pivot mechanism originally proposed by Reed [1]. The aim of the new concept presented in this work is to replace the passive spring-damper elements with an active element, namely, a piezoceramic strut that consists of a series of thin circular plates laminated on opposite faces with piezoceramic material. The poled directions of the piezoceramics are aligned so that a voltage applied across the element contracts on one side and expands on the other. The plate bending is then translated into an axial motion along the strut. Modern state-space based controllers have been implemented for the first time in literature to study the various performance and stability issues of the proposed concept. The overall conclusion reached of this simulation study is that an active wing/store flutter suppression system using a robust control law based on *H*- infinity theory yields relatively favorable results when compared to an uncompensated passive decoupler pylon mounted, store-flutter-suppression system. The favorable results include robustness of the system to modeling uncertainties and an increase in performance in terms of disturbance rejection, noise attenuation, and insensitiveness to parameter variations. Further, preliminary simulation study of the plant with a robust adaptive controller indicated that on comparison with the passive wing/store flutter suppression system, an increase in performance and stability can be obtained during store release event which is crucial during combat maneuvers of an aircraft.

Accomplishments:

Conclusions of the research performed under this grant are:

1. Use of an active strut as a decoupler pylon increases the wing/store flutter speed substantially over that of a rigidly attached store, provided the strut's stiffness property satisfies Reed's criterion.

2. Coupled with an appropriate controller, the system is shown to have increased performance in terms of withstanding parameter variations, rejecting unwanted output disturbances, attenuation of noises, and more importantly an increased robust stability margin for uncertainties in modeling errors.

3. The *H*-Infinity controller compensated system demonstrated better overall performance and robust stability over LQG/LTR controller, under approximately the same given maximum control-energy constraint. The *H*-Infinity theory based controller has the advantage of assigning weights more intuitively by means of sensitivity and complimentary sensitivity weights whose realm of action is restricted to frequency ranges that are typically independent of each other.

4. An approximate multiplicitive uncertainty model, derived to represent the error due to neglecting store aerodynamics, appears to be an effective tool in analyzing the robust stability of the closed-loop wing/store flutter model.

5. Preliminary investigations with robust adaptive controller based on gradient law and linear quadratic controller has shown promising results in terms of the ability of system to track unknown parameters as well maintaining performance and stability in the presence of multiplicative uncertainties during store release event.

Detailed contributions and key conclusions of this research are discussed in the Ph.D. Dissertation resulting from this effort and the corresponding journal and conference publications listed below. A summary of these publications follows.

The research is based on a typical section model used for the structural model of the wing and a two-dimensional incompressible aerodynamic theory used to model the aeroloads around the wing. However the aerodynamics around the store are neglected. Rather the store aerodynamics are considered by analyzing the system using a multiplicative uncertainty model. The model is derived assuming that the aerodynamics around the wing and the store can be equivalently captured by a modified Jones' rational approximation. The only forces and moments acting on the store are due to the actuator which acts as an active decoupler pylon. The active decoupler pylon consists of a piezoceramic strut which acts both as a load carrying tie between the wing and the store as well as an actuator. The actuator provides the necessary moments at the wing and the store end to maintain the alignment between them while at the same time acting as a soft spring to isolate the wing pitch from store pitch inertia effects. The forces and moments induced by the actuator are incorporated into the equations by the principle of virtual work. The equations of motion are converted into state-space equations via the use of Jones' approximation for the Theodorsen function describing the circulatory aerodynamics around the wing.
Open-loop simulations using the wing/store parameters corresponding of an F-16 aircraft carrying a GBU/8 store configuration were used for the study throughout. The results indicate a 14.86% increase in flutter speed with the decoupler pylon over that of a bare wing and a 33.86% increase over a rigidly attached store.

A linear quadratic optimal controller is designed for the single-input multi-output (SIMO). A Loop Transfer Recovery (LTR) algorithm based controller yielded a 350% stability margin around the flutter frequency (25 rad/sec) that is necessary to alleviate any concerns about robustness of the system due to uncertainty in higher dynamic modes. In terms of nominal performance, although the LQG/LTR compensated system demonstrated faster time responses and satisfactory noise attenuation properties at the outputs, the effect of sinusoidal input disturbances have not been able to get rejected. This has been illustrated by an example wherein a sinusoidal input disturbances with frequency 6 rad/sec has been shown to make a negligible reduction in the output response. Similarly the output sensitivity properties have been found to be satisfactory at the output (plunging motion), but the pitch angle outputs did not show any improvement

in sensitivity properties. This may be potentially dangerous to the actuator because it may not be able to withstand the perturbations and may result in physical failure of the strut due to resulting excessive tension or compression. These results are discussed in detail in [3]

A controller for the wing/store flutter problem is designed using the Glover-Doyle algorithm of the *H*-Infinity theory which solved the minimization of a stacked objective. In particular, the simultaneous minimization (in appropriate frequency range) of the weighted output sensitivity and complementary sensitivity transfer matrices is solved. The weights were chosen based on the requirements that the output errors entering within the close range flutter frequency range (< 30 rad/sec) be rejected by 10:1 margin (with respect to that of the open-loop system). In addition, a 40-dB/decade closed-loop roll rate be achieved at higher frequencies that ensures acceptable sufficient stability margins and acceptable noise attenuation. While the cost functions corresponding to the three outputs met the infinity norm objective (< 1) at higher frequencies, the cost functions corresponding to outputs neither meet nor violate the objective at lower to mid frequency ranges. This is a potential cause for concern because at low frequencies the sensitivity margins at the pitch angles will not be sufficient enough to withstand parameter variations. This resulting free-play between wing and the store will cause actuator failure. This could perhaps be avoided by appropriate choosing unequal weights at the three output channels.

By reflecting the uncertainties at the output of the plant, the tolerance margin around the flutter frequency was observed to be $\pm$ 298%. This magnitude of margin is essential for enduring modeling errors such as those due to store aerodynamics and other flexible modes. A typical time response, comparing the perturbed open- and closed-loop system, indicate the effectiveness of the controller to suppress flutter. Several other nominal performance measures including noise attenuation, input disturbance rejection, etc have been found to be satisfactory. The details of this result can be found in [4].

Next, an indirect adaptive robust control algorithm based controller was designed for a SISO wing/store model. The algorithm consists of an adaptive law that is based on gradient method modified (with leakage and switching-sigma algorithms) to make the closed-loop system more robust to uncertainties and parameter variations. The feedback control loop consists of a linear quadratic adaptive controller that uses the estimated plant parameters to construct a state observer gain matrix. A linear quadratic regulator law is then used to construct the state feedback gain matrix adaptively. The effectiveness of the designed adaptive controller is varied by simulating a sudden change in store mass parameter (at sub-critical flutter speed) simulating the real life situation of an ejection of a bomb out of an under wing external rack. The on-line estimator performed very well in tracking the uncertain plant parameter coefficients to a small percentage error of their true value. The controller also demonstrated an improvement in performance over the open-loop response in terms of faster settling time and smaller steady-state amplitude. Moreover, the presence of an input multiplicative uncertainty model had no effect on the stability of the closed-loop system while it caused the open-loop system response to

diverge. This type of robustness is especially critical during combat maneuvers. The results of this phase of the research are presented in [5].

Following the encouraging results derived from the fundamental aerodynamic model a three dimensional aerodynamic approach is worked out. From flight test and windtunnel data it is known that the aerodynamics on store and pylon can play a significant role, in particular when steady state assumptions are inadmissible. Underwing installations are a frequent source of aerodynamic interference resulting in increased drag. Pitch and yaw oscillations of pylon/store combinations bring about unsteady airloads and occasionally lead to store leading-edge separation. Phenomena like these inspire substantial changes in flutter bounderies and flight characteristics of aircrafts and their understanding is central in designing a successful wing/store flutter suppression system.

Therefore, a comprehensive 3D aerodynamic model is employed to capture most of the anticipated flow effects. The method of choice is a unsteady vortex-lattice method (UVLM) which promises to produce accurate results in the low transonic flow regions where shock waves and turbulent flow do not dominate. The vortex method implicitly models the vorticity captured in boundary layers and the process of vortex shedding which is a physical occurrence and can sometimes be observed by the naked eye. The UVLM is qualified of modeling the flow phenomena mentioned above and has proven its reliability and accuracy in the literature.

Among the many UVLM variations employed in the field of flow simulations the one chosen here has been developed by Mook et al.. It enables the researcher to treat the mechanical and aerodynamic models as independent entities and then to merge the individually optimized models to a combined set of equations which is solved iteratively in time. Consequently, limit cycle oscillations (LCO) that are largely due to nonlinearities in the structure can be investigated as easily as non-linearites stemming from the aerodynamics.

The aim of this research project is to investigate the effect of underwing bodies with respect to flutter characteristics, limit cycle behavior, and store separation. It is intended to provide the specifications required to design a piezoelectric actuation scheme to suppress flutter as well as LCO and to control store separation.

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Dr. Inman visited and consulted with Ben Shirley and Ed Anderson of Eglin Air Force Base in conjunction with store flutter problems. They provided data and were very helpful in formulating the problem, for which we are grateful.

During the three year period of this grant, Dr. Inman gave over 50 oral presentations at various conferences, workshops and public seminars. In addition, P. Gade gave four lectures at four different conferences. Dr. Inman also gave seven key note addresses at a variety of conferences through out the world.